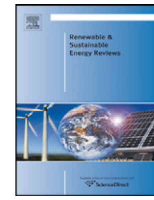
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Summer thermal behaviour of compact single family housing in a temperate climate in Argentina

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This paper analyses the thermal-energy behaviour and the comfort/discomfort conditions in four compact massive housing located in a temperate climate in the central region of Argentina. The study has the following main objectives: (a) the thermal and energy monitoring of compact single family housing with the same technology, with different orientations, along the same period of summer 2010; (b) the statistical analysis of the indoor temperature behaviour, comfort conditions and electricity consumption for a historical period; and (c) the extrapolation of the results obtained in one of the studied dwellings to a sector of the neighbourhood. The analysis for summer showed that these houses would not reach indoor conditions of thermal comfort without using mechanical air conditioning. Monthly energy consumption average, summer consumption and February consumption for the historical period 2000–2009 were obtained. The average and a statistical analysis of the collected data revealed a normal distribution for the series. When monitoring results from 2010 were added to the statistical analysis, it was observed that the annual behaviour is similar to that of 2009 except for one of the houses in which the increase in consumption is the result of adding a split air conditioner. Extrapolation of results to houses in another block allowed us to infer – by analyzing electricity consumption patterns – that dwellers did not live in comfortable conditions. The addition of insulation on the roof was studied as a strategy to improve indoor conditions and reduce energy consumption. The cooling load, by assuming an indoor temperature of 25 °C, of a house with a thermally improved roof would reach energy savings of around 18%, figure that can be considered highly promising for a growing city.

Contents

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1. Introduction

In our oil-dependent societies, energy constitutes a very important part of the ecological footprint and it is responsible for 80% of CO_2 emissions. Energy matters are, as well, intimately related to climatic and environmental crises. The IPCC, a UN scientific agency on climatic change, pointed out that the planet's global warming with respect to pre-industrial levels will bring about unpredictable climatic change consequences. To avoid an increase of mean temperatures, the agency recommends that the concentration of greenhouse gases in the atmosphere stabilize at a level below 450 parts per million of equivalent CO_2. The world must turn towards a low-carbon economy, whose products and services reduce considerably the CO_2 emissions. This makes necessary to transform the current energy-use model and the production/consumption model as well. In the building sector, optimizing solar energy use, thermal insulation, ventilation control and heat exchange might allow to reduce the energy demand for climatisation to values around 10–15 kWh/m^2. In order to obtain a reduction of energy consumption in the building sector, it will be necessary to adjust energy demands and equipment efficiency to improve thermal and environmental indoor conditions. Following the results of the report issued by the Program *Cambio Global España 2020/50* [1] it can be thought that a strong *decarbonization* of the building sector with its *re-configuration* on the basis of the bioclimatic rehabilitation of the cities built environment may be possible. In previous studies, the IPCC [2] considered that the design strategies of energy efficient buildings with a high-quality indoor environment have to be oriented towards a reduction of heating and cooling loads, to an efficient use of electrical appliances, and to the choice of systems that use energy resources efficiently, amongst other strategies.

Why should we pay attention to indoor temperature quality during the design phase of a building? Because it relates human beings to their living and work environments. People spend more than 80% of their lives inside buildings. It is also important to carry out an evaluation of their energy-environmental performance [3]. Ratti et al. [4,5] maintain that a building is a structurally integrated entity, both from the functional as well as from the environmental points of view. Improving its energy performance requires a detailed study and also the simulation of its behaviour, considering at the same time, the phenomena that occur at an urban level.

For these authors, energy performance depends on urban geometry, on the building's own design, on systems' efficiency and mainly on the dwellers' behaviour. Peeters et al. [6] consider that in residential buildings, indoor conditions are far from being balanced: both, the type of activity and the clothing used, may vary within short time periods, indoor gains and energy contributions may fluctuate, affecting rapidly indoor temperatures. Occupancy variations will incide, amongst other things, on the required ventilantion rates. Dixit et al. [7] stated that current building practices regarding design, techniques and production technologies demand urgent revision and change in order to optimize energy consumption. Liu et al. [3] conclude that, to design a low energy consumption building, new types of knowledge together with the development of new materials, technologies and systems constitute an imperative. Energy efficiency, however, depends on such technologies as well as on users' options and on policies affecting decision-making [8].

The premonitory vision of the architect Buckminster Fuller, regarding the finite nature of world resources dates back to the end of 1920 [9]. But it was only in 1973, as a result of the high oil prices, when energy conservation strategies appeared to be part of the environmental agenda. The building sector is particularly under pressure: approximately half of the world's resources are destined to condition indoor environments. The building sector constitutes itself one of the main protagonists of the environmental problems due to the over-use of non-renewable resources, land use and energy consumption along the life-cycle of a building. Ürge-Vorsatz and Novikova [10] stated that during 2004, 37% of the world's energy were used by buildings, and this figure will reach 42% by 2030. In Europe during 2000, 45% of the produced energy were used by the building sector and 50% of the generated pollution had its origin in the same sector [11].

In Argentina, and according to the Greenhouse Effect Gases Inventory, for the year 2000, 91% of CO_2 emissions from the energy sector were originated by fuel burning, the remaining 9% was due to fugitive emissions. Energy industries were responsible for 30.0% of those emissions, freight transportation for 18.2% and the residential sector for 14.4%, amongst others. Between 1990 and 2000 there was a 28% emissions' increase, with an accumulated annual rate of 2.5%. The two sectors with higher shares in the total net consumption were the residential one (which rose from 13.6% CFT – total final consumption – in 1970 to 19.4% in 2003) and the commercial and public one (2.6% in 1970 to 6.7% in 2003). These consumption rates are directly related to meeting energy household and services' needs and they had increased, mostly, due to the use of natural gas, which substituted other sources and increased the specific consumption related to caloric use (cooking, water heating, air heating). Regarding fuels' share in CO_2 emissions in the residential sector, natural gas takes up 81.1% [12].

The use of non-conventional energy sources, the energy perspective in Argentina and the possibility to revise Regulations and Building Codes in Argentina, led many authors towards an evaluation of residential buildings in order to analyze the thermal-energy behaviour, comfort conditions, energy consumption and users/dwellers' behaviour [13–27]. The authors of the present work assume the importance of the increased purchase of air-conditioning devices (according to figures provided by INDEC there was a 12.6% increase in 2008), and the tendency towards increased housing construction rates [28].

In this context, the aim of the present work is to analyse the thermal-energy behaviour and the comfort/discomfort conditions in four compact massive houses built in Santa Rosa, a city located in a temperate climate in the central region of Argentina. The houses are representative of a typology that prevails in different neighbourhoods of the city.

The main objectives of this study are:

a. the thermal and energy monitoring of housing with the same typology and technology and different orientations, along the same period of the summer 2010,
b. the statistical analysis of the indoor temperature behaviour, comfort conditions, and electricity consumption for a historical period (2000–2009) and also including the year 2010, and
c. the extrapolation of results obtained in one of the studied dwellings to a sector of the neighbourhood.

2. Location of buildings

Much of the territory of the province of La Pampa is part of the vast Pampas plains, a transition area located towards the East of the Cuyo region and North of Patagonia, with a height above sea level between 600 and 1100 m, temperate climate, and rain levels exceeding 500 mm per year in the NE with values decreasing towards the West.

The city of Santa Rosa (capital of the province of La Pampa) is located in a cold temperate climate. Fig. 1 shows the location of the province of La Pampa and the plan and the panoramic view of the city of Santa Rosa. The mean and absolute minimum temperatures during July are −11.2 and 7.6 °C, respectively. The annual heating degree-days (base temperature = 18 °C) is 1545 (see Table 1). Santa

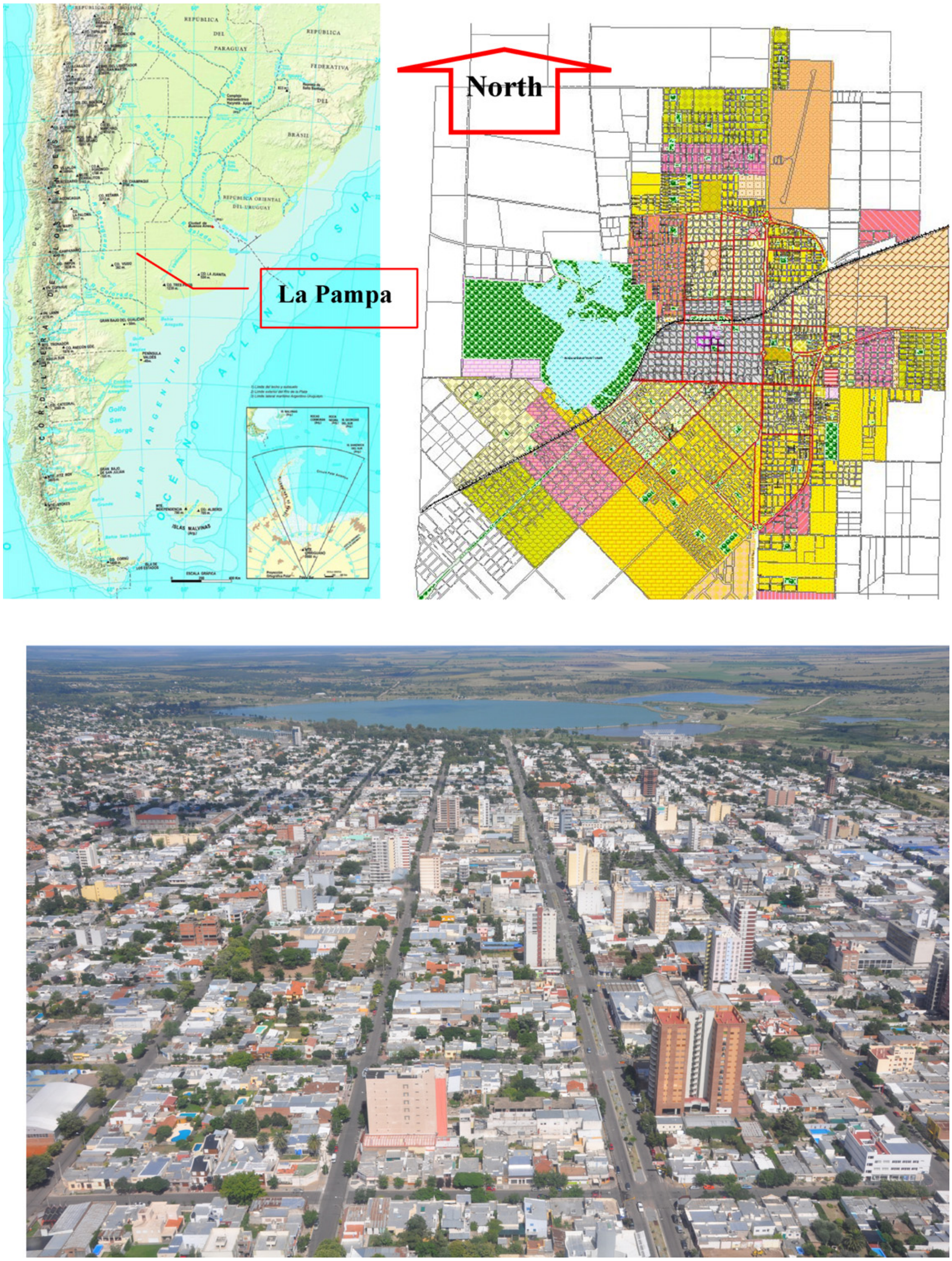
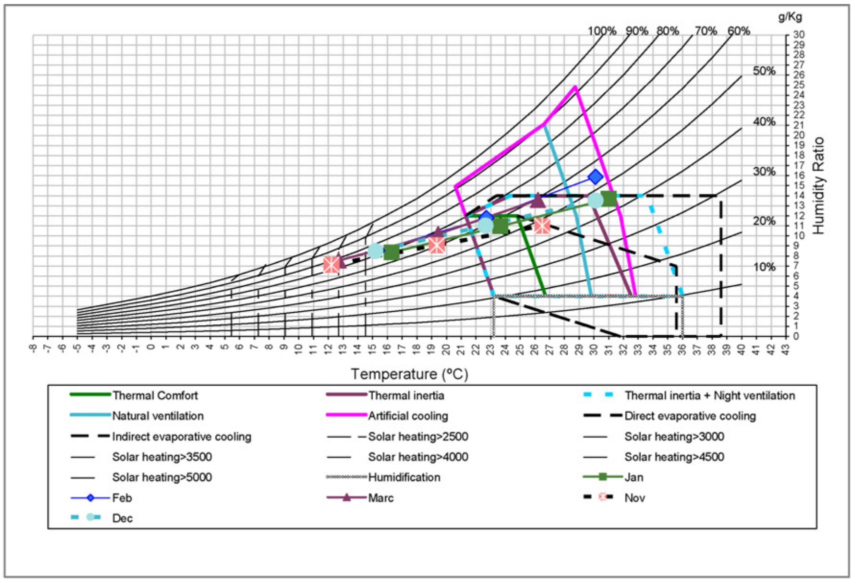


Fig. 1. Location of the province of La Pampa. Plan and panoramic view of the city of Santa Rosa.

Rosa has more than 100,000 inhabitants and in recent years there was an evident growth of new buildings construction, especially towers of multifamily housing with large glazed areas without sunscreens. Between 2005 and 2007 new construction developments increased around 24% (85% are apartment towers). Building refurbishment and enlargement grew about 42.8% (INDEC, 2011) [31]. As stated above, this rate is similar to the values found in other urban centres of the country. From the energy point of view, an increase in power consumption in the city (electricity and natural gas) has been recorded in the residential sector. According to the Electricity Company, the electricity consumed was mainly used in the domestic sector. The consumption-per-user rate increased 5.6% between 2008 and 2009, with an average annual consumption of electricity of 2380 kWh per-user [32]. According to the Gas Distribution Company, around 67% of the natural gas consumed annually, and around 75% of the gas consumed during winter, is used to heat buildings. The average annual natural gas consumption per-user is 1420 m^3 [33].

Bioclimatic design is one of the best approaches to reduce the energy cost in buildings. Proper design is the first defensive



hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
Total	9	9	9	0	0	0	0	0	0	0	8	9

% of shading: 25

Fig. 2. Design' recomendations and shading requirements.

barrier against the stress of the climate. Buildings should be designed according to the climate of the site in order to reduce the need for mechanical cooling or heating. Hence, maximum natural energy can be used for creating a pleasant environment inside the built envelope [34]. A simplified PC software was developed by Gonzalo [35] that allows to propose the most appropriate building's bioclimatic design strategies on the basis of monthly mean temperature and relative humidity data, and to roughly estimate hourly cooling and heating needs. The comfort temperature T_n (°C) is determined in the software by using the mean annual temperature T_m (°C) of the location, through the expression $T_n = 17.8\,°C + 0.31\,T_m$. The comfort zone can be expressed as $T_n - 2.5\,°C$ to $T_n + 2.5\,°C$ [36].

Fig. 2 shows the psychrometric chart and shading requirements in summer for Santa Rosa. It can be observed that only the mean values (temperature and relative humidity) corresponding to December, January and February fall into the comfort area. Both November and March would need some solar heating to reach the comfort area. Considering the maximum mean temperatures of December, January and February, it is evident that mechanical cooling would be needed. In November and March, thermal inertia, natural ventilation and night ventilation would be sufficient. In the case of minimum mean temperature values (maximum humidity), solar energy would be needed to heat indoor air and to reach the comfort area in all months. During November and March, values of about 3500 W/m^2 over a vertical surface facing north would be needed to reach comfort. During 25% of the year the buildings need to be protected against solar irradiance. In January, February, March and December, from 11 am to 7 pm, and between 12 am and 7 pm during November, the façades of buildings should be shaded to avoid overheating.

Table 1
Climatic data of Santa Rosa, La Pampa, Argentina (36°57′S, 64°27′W, 189 m.a.s.l.)..

Annual values	Maximum		23.4 °C
	Minimum	Mean temperature	8.1 °C
	Mean		15.5 °C
	Global horizontal irradiance (*)		16.3 MJ/m^2
	Relative humidity		68%
July	Minimum		1.5 °C
	Mean	Mean temperature	7.6 °C
	Maximum		13.5 °C
	Thermal amplitude		12.0 °C
	Mean wind velocity		2.8 m/s
	Global horizontal irradiance (*)		8.1 MJ/m^2
	Mean ground temperature (−1.00 m)		10.0 °C
January	Maximum		31.9 °C
	Mean	Mean temperature	23.8 °C
	Minimum		15 °C
	Thermal amplitude		16.9 °C
	Mean wind velocity		3.9 m/s
	Global horizontal irradiance (*)		24.0 MJ/m^2
	Mean ground temperature (−1.00 m)		23.8 °C
Annual heating degree-days (Tb = 16 °C)			1136
Annual heating degree-days (Tb = 18 °C)			1545
July–August heating degree-days (Tb = 16 °C)			939
Annual cooling degree days (Tb = 23 °C)			128

Source: Servicio Meteorológico Nacional – Fuerza Aérea Argentina (National Forecasting Service – Argentine Air Force) (period = 1990–1999) [29]. (*) Grossi Gallegos and Righini [30].

3. Architectural description of the studied housing

3.1. Common features

Four houses located in low-density neighbourhoods – “Villa Alonso” and “Villa del Busto” – were selected for this study. C1 and C2 houses are located in “Villa Alonso” and C3 and C4 in “Villa del Busto”. Figs. 3 and 4 show the airplane mapping of a sector of the neighbourhoods and Fig. 5 shows the studied houses.

The houses are compact, one-story buildings between party walls and without thermal-insulated envelope. Exterior walls are built of 0.30 m thick massive bricks. The thermal transmittance *K* is 1.88 W/(m^2 °C). IRAM Norm 11605 (1996) [37] recommends maximum values of *K* for walls and roofs that is related to the different bio-environmental areas of the country. These values correspond to three higrothermal comfort levels (A, B and C). In the houses under study, the walls’ *K* value reaches the less demanding level (Level C, *K* = 2.00 W/m^2 °C). The resistent roof structure in houses C3 and C4 is made of an iron frame and solid brick, whereas in C1 and C2 there is a frame of prestressed tie beams, ceramic bricks and a concrete compression layer. On top of the structure there is a sloped subfloor of 0.1 m average thickness, water-resistant membrane, except for C2 which has a massive roof with French tiles attached with plaster. Thermal transmittance is 1.52 W/(m^2 °C), value that is higher than the one recommended by the same Norm (*K* between 0.19 and 0.76, for levels A and C, respectively). The windows in all the four houses have roller shutters and simple glazing. In C1, C3 and C4 the window frames are made of solid wood, in C2 they are made of pre-painted aluminum. The exposure factor, defined as the relationship between outdoor envelope’s surface without party wall and outdoor envelope’s surface is higher in C2 (73%) because it has a west wall facing outdoors. The compactness index, defined as the relationship between perimeter of circle and perimeter of the project varies between 57 and 73%.

3.2. Detailed description of each house

C1 has its main façade and entrance door facing north. Food cooking and heating were carried out by means of a gas and/or microwave oven in a multi-purpose room, which is connected to



Fig. 3. Single family housing and a sector of the neighbourhood ‘Villa Alonso Norte’.

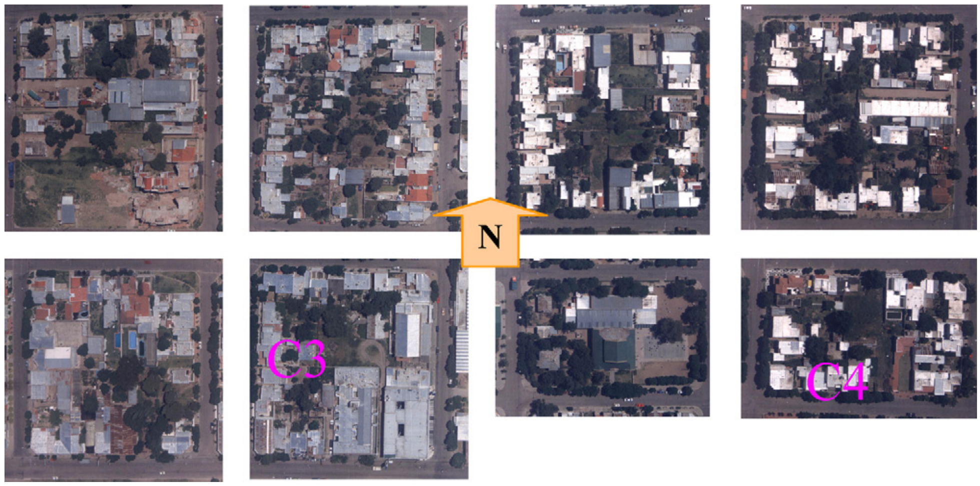


Fig. 4. Single family housing and a different sectors of the neighbourhood 1Villa del Busto'.

the house through a circulation area with a glass balcony-door facing SW and an outdoor vertical awning which remains closed during the afternoon as it is shown in Fig. 5. The entrance door to the multipurpose room from the dinning-room can also be observed in that same figure (left). The house has two air-conditioners, one in the kitchen-dinning-room and the other in the southern bedroom on the party wall.

C2 house has its walls facing west, south and north (the party wall faces east). It has a multipurpose room, separated from the house, and a wide glass area without solar protection which allows the sun to reach the functional areas from the SW (Fig. 5).

C3 has its main façade facing west. The west walls are not sufficiently shaded by the trees and they receive 13.5 MJ/m^2 of solar irradiance according to the Liu-Jordan model (daily irradiance over horizontal surface = 20.8 MJ/m^2) during clear sky days without shading.

C4 shows its main façade and entrance door facing south. The two rooms with windows facing north are covered by pergolas with deciduous forest cover and therefore have shade during the summer. The house has a 2300 frig air split conditioner located in the bedroom whose outdoor wall faces east (average daily use of approximately 1 h).

4. Thermal and energy monitoring under real conditions of use

4.1. Period: February 5th to 17th, 2010

The houses were monitored from January 28th, 2010 to February 22nd of the same year. Data-loggers HOBO models U8 and U12 were used to sense indoor temperature and relative humidity. They were placed in the functional areas of each house. Meteorological variables were registered at roof level of one of the houses by means of an autonomous meteorological micro-station HOBO H21 with a photovoltaic solar irradiance sensor. The period between February 5th and 17th was selected for the analysis, which was characterized by a sequence of clear sky days and solar irradiance of about 900 W/m^2 at solar noon, with a maximum wind speed of 5.5 m/s (Fig. 6). The mean outdoor air temperature was 23.3 °C, with minimum temperatures of 15 °C and maximum temperatures overpassing 30 °C. On February 10th, the outdoor temperature reached 35 °C, 2 °C below the absolute maximum temperature for the last decade.

Fig. 7 shows the average indoor temperature of each house. During the studied period, the average indoor temperature obtained from the monitored data was 25 °C, 1.7 °C above the outdoor mean temperature. During the monitoring period it was occupied by a couple and their university student daughter. During periods of high solar irradiation levels, the roller shutters in the sitting-room and bedroom windows facing north, and bedrooms facing south were kept down. Indoor temperature decrease coincided with an increase in wind velocity and this occurred on February 12th (4.5 m/s) reaching 22.6 °C on February 17th when wind velocity reached 5 m/s and minimum outdoor temperature was 15 °C (Fig. 6). The recorded daily average electricity consumption was 11.8 kWh (0.08 kWh/m^2), 80% higher than the neighbourhood historical average value recorded during February (6.6 kWh) [32].

In C2, the average indoor temperature was 26.2 °C, without mechanical conditioning. This value is 2.9 °C higher than the mean outdoor air temperature. Its owner is a retired woman who remains at home most of the day. During summer, she takes advantage of the very good cross-ventilation produced between both bedrooms (one facing north and the other facing south), and also between the dinning room and the laundry area, rooms which have windows facing north and south respectively. As it happened with the previous case, a decrease in outdoor temperature, lower solar irradiance and an increase in wind velocity allowed for better indoor thermal conditions since February 12th. The recorded and consumed electricity daily average was 6.5 kWh (0.07 kWh/m^2), a value similar to the historical daily average consumption in the neighbourhood for the same month.

The most unfavourable situation was detected in the C3 house. The house is occupied by two active adult persons who are out of the house for about 8–10 h a day. After six days of high temperature and solar irradiance, indoor temperature reached 30 °C and it only began to decrease on February 16th due to the decrease in solar irradiance (400 W/m^2). Indoor temperature reached a minimum value of 15 °C. The average indoor temperature was 28.1 °C, 4.8 °C higher than the mean outdoor air temperature. The house has a ceiling fan which is turned on only when the room is being used. According to the description provided by the dwellers, the windows are kept closed during the nights and opened at early morning, only if outdoor conditions are favourable. They were kept closed during the days with strong winds and suspended dust. The recorded electricity daily consumption was 3.9 kWh (0.056 kWh/m^2), which corresponds to 59% of the energy daily average consumed in the neighbourhood (6.6 kWh).

The last house in our study shows its main façade and entrance door facing south (C4). Its dwellers are two elderly women, one of them is retired, the other one still active. The average indoor temperature was 26.0 °C, 2.7 °C higher than the outdoor average temperature. Towards the end of the study period this house, too,



Fig. 5. Plant and view of the studied houses.

showed a decrease in the indoor temperature average, so the arguments provided for the previous cases are also valid for this one. The daily electricity average consumption was 5.6 kWh (0.07 kWh/m^2), 15% lower than the historical average in the neighbourhood.

4.2. Period: February 8th to 10th, 2010

The hourly temperatures in the zones of the four houses are analyzed for three sunny days of the period. The selected days are February 8th to 10th, when the maximum outdoor temperatures of the period were recorded, reaching 35 °C. Solar irradiance on horizontal surface reached 900 W/m^2 at solar noon, and mean wind velocity was around 3 m/s (Fig. 6). Fig. 8 shows the evolution of temperature in each of the functional areas of the C1 house (main façade north). The warmest rooms were the multipurpose room with a window to the north leading to an indoor yard, and the kitchen/dinning-room with a balcony door to the SW with an outdoor awning which is lowered at 10 am and raised at 7 pm (Fig. 5). The multipurpose room reached a maximum temperature of 30 °C when the outdoor temperature average was 28.2 °C. During February 9, an increase in temperature during lunch and dinner times in the kitchen/dinning-room area can be observed in the

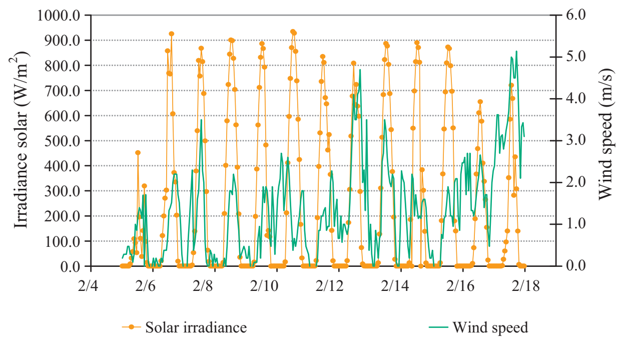


Fig. 6. Solar irradiance on horizontal surface and wind speed for the period between February 5th and February 17th.

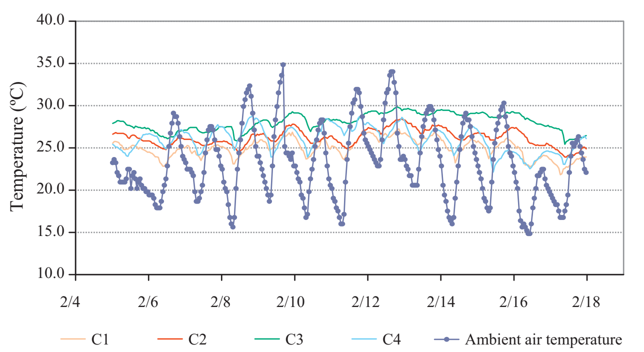


Fig. 7. Outdoor and the houses' average indoor temperature for the period between February 5th and February 17th.

figure. Both bedrooms facing south and the living-room showed a mean temperature of 25.2 °C, 25.4 °C and 25.5 °C, respectively. The coldest zone of the house was the bedroom facing north, with a mean temperature of 21.7 °C, due to the protection of an 1.50 m eave, and the shading of a roller shutter that was kept down since 9:30 am.

Fig. 9 shows the thermal behaviour of the C2 house. The high exposure of the multipurpose room's transparent area to the south-west (see Fig. 5) produces an increase in the indoor temperature of the barbecue hut, which reached 33.6 °C at 4 pm, at a time when the outdoor temperature had reached its maximum peak. This part of the house was not used during the monitoring period. Passive cooling through crossed ventilation, watering green spaces at adequate times, and house compactness, all three factors contributed to keep comfort conditions during most of the monitoring time.

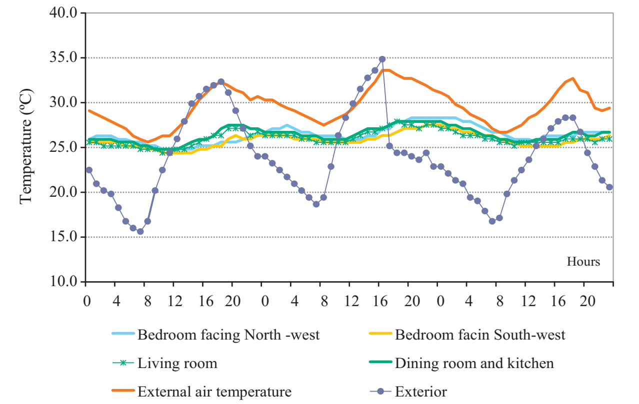


Fig. 9. External air temperature and thermal behaviour of C2 for the period between February 8th February 10th.

Fig. 10 shows the thermal behaviour of the C3 house. In previous paragraphs we stated that this house showed the most unfavourable thermal situation, only 17.6% of the indoor temperature average was below 27 °C. The western bedroom was the warmest room, amongst other reasons, because of the irradiance over its outdoor envelope. On February 9, both in this bedroom and in the sitting-room, the temperatures reached 30 °C, 5° below the outdoor maximum. The figure shows a time lag of almost 8 h between the moment of maximum outdoor temperature (4 pm) and the maximum indoor temperature (2 am). The figure shows that the wind, which began to blow on February 9 at 9 pm and kept blowing for more than 12 h – mean velocity of 2.5 m/s – produced a decrease in indoor temperature of about 3 °C, what clearly exemplifies the effect of thermal inertia combined with ventilation during the early morning (6:00 am to 9:00 am) as a result of opening windows for cleaning purposes.

In the C4 house, both bedrooms have their windows with rolling shutters facing north. The pergola that protects its envelope from solar irradiance also favours natural conditioning of the environment in this sector. Fig. 11 shows the thermal behaviour of the C4 house. The figure shows a time lag of almost 11 h between the maximum indoor and outdoor temperature. The bedroom with its window facing north and an exterior wall facing east, has a 2300 frig split conditioner which, on February 8, was turned on at 9:00 pm (the curve shows a decrease of 1 °C). This house has an indoor temperature thermal amplitude of almost 5 °C, 2 °C above what was shown for C3, whose indoor temperature never decreased below 25 °C.

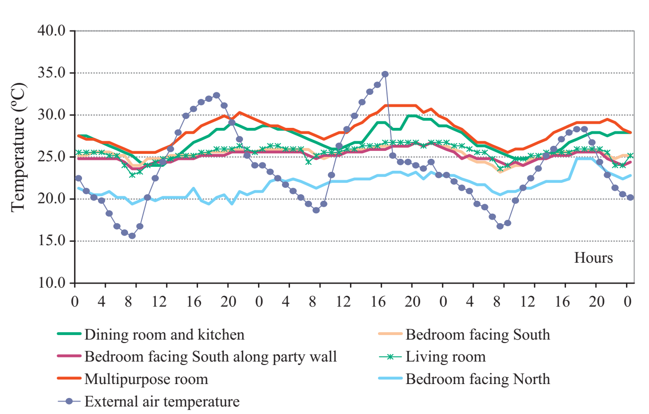


Fig. 8. External air temperature and thermal behaviour of C1 for the period between February 8th and February 10th.

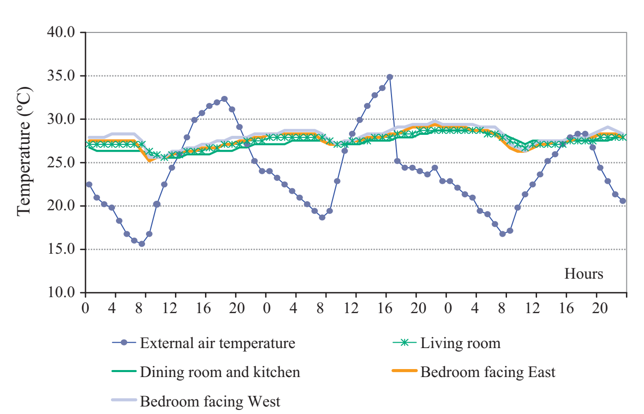


Fig. 10. External air temperature and thermal behaviour of C3 for the period between February 8th and February 10th.

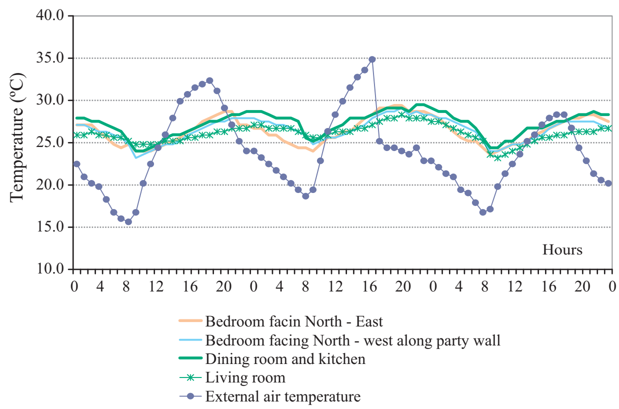


Fig. 11. External air temperature and thermal behaviour of C4, C1 for the period between February 8th and February 10th.

4.3. Accumulated relative frequency

The percentage of records that fell within the comfort zone (up to 26.5 °C according to Fig. 2) was analyzed for each house. With the hourly temperature data for each functional area, an accumulated relative frequency statistical analysis was carried out. Fig. 12 shows the results for the C1 house (with electrical air conditioner). Temperature in the bedrooms is between 90 and 100% below 26.5 °C. The bedroom facing SW has an air conditioner, the one facing NW is shaded by a balcony-eave and its west wall is not exposed because it is shared with the neighbouring house. Temperature in the sitting room 80% of the time was not beyond the recommended value. The kitchen, which is integrated into the dinning-room, is one of the warmest zones, with mechanical air conditioning, and what is more, with the dwellers habit of not cooking in the area. They cook their meals in the multipurpose room which is only connected to the previous area by a door. Temperature in the garage was found to be below 26.5 °C 45% of the time. This area has a solid entrance door facing north, and it is a space that continues to the south and joins the kitchen and dinning-room. It is evident that this 16 m long area does not have the necessary ventilation.

Fig. 13 shows the statistical analysis of the temperature accumulated frequency recorded in C2. It should be noted that this house does not have mechanical air conditioning. In the cross-ventilated bedrooms, from 70% to 80% of the time, the temperature does not go beyond 26.5 °C. In both cases, the maximum temperature reaches 35 °C and decreases to 20 °C. The behaviour is somewhat better in the bedroom facing SW, maybe due to the fact that its window has less exposure to solar radiation. During 70% of the time, the sitting-room has a temperature below 26.5 °C and a maximum one of 33 °C. Of the functional areas which are mostly used, the kitchen/dining-room is the one which reaches the highest maximum temperature (36 °C), though 80% of the time, temperature is below 26.5 °C. According to a comment made by its dweller, she uses a microwave oven to avoid turning on the gas stove and she is also used to cross-ventilating rooms at adequate times.

According to monitoring and statistical analysis' results, thermal behaviour was more unfavourable in the C3 house without mechanical conditioning and a façade facing west without sufficient solar protection. Temperature in both bedrooms varied between 24 and 32 °C (facing east) and between 25 and 31 °C (facing west), and only 15% of the time it was below the maximum recommended limit. Even though the maximum temperature was lower than that in C2, the minimum temperature was 4 and 5 °C higher, maybe due to scarce natural ventilation- windows remain mostly closed as it was previously explained. Both in the living-room as well as in the kitchen/dining-room, users would be 90% of the time, according to the relevant charts, in a state of discomfort (Fig. 14).

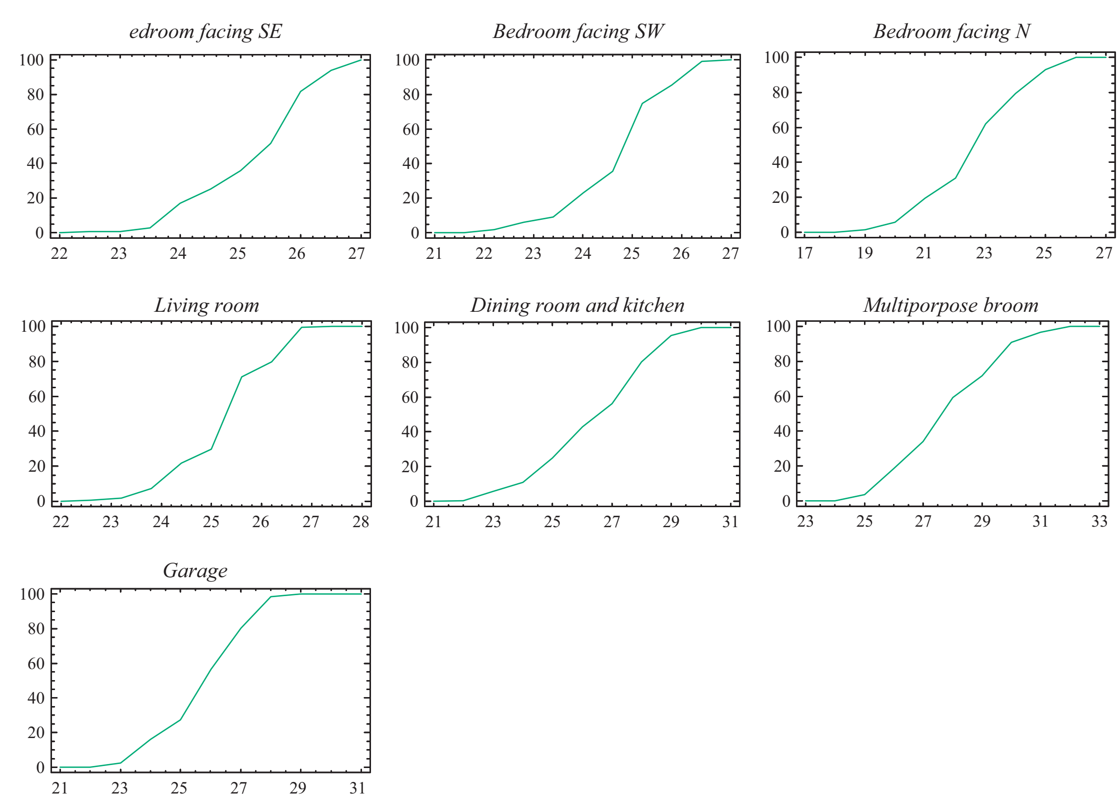


Fig. 12. Percentage of hours with temperatures higher than 26.5 °C in C1.

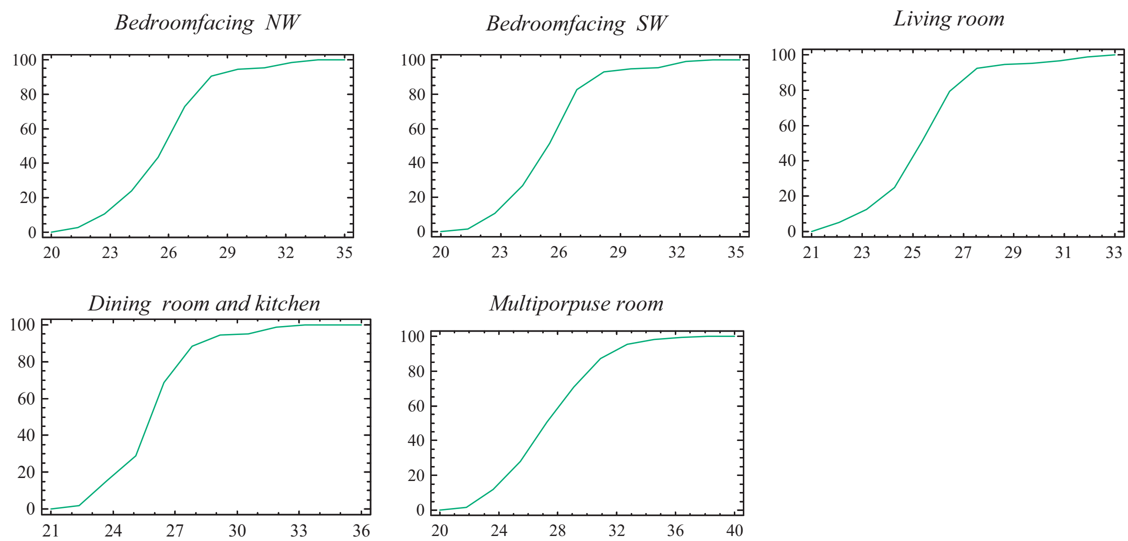


Fig. 13. Percentage of hours with temperatures higher than 26.5 °C in C2.

In the C4 house, both bedrooms (facing north) shaded by a pergola had temperatures below the comfort limit during 60% of the time. As it is expected, in the kitchen/dinning-room (facing south) with indoor important loads, this value decreases to 40%. Temperature recorded in the sitting-room (facing south) and over the west party wall (no exposure to solar irradiation) with closed roller shutter during the sunlight hours, was 70% of the time below 26.5 °C (Fig. 15).

5. Analysis of historical energy consumption and of February 2010

During the first phase of the study, real electricity consumption bills corresponding to the four houses (period 2000–2009 for C1, C2, C4; period 2005–2009 for C3-rented by the same dweller-) were analyzed. During the second phase, 2010 data were added, year during which the summer thermal-energy monitoring was carried out.

Table 2 shows electricity annual consumption in C1 with an average value of 3125.1 kWh and a variation coefficient of 8.1% along the period. In the same table it can be observed the monthly average consumption and its deviation from the mean, which varied between 11.4% and 31.5%, years 2000 and 2008, respectively. Table 3 shows the monthly average consumption between 2000 and 2009. The greatest dispersion is observed during the warm periods. The highest average consumption corresponds to January (330.7 kWh) and February (299.8 kWh), with a variation coefficient of 18.1 and 20.8%. The highest absolute maximum temperatures averages were recorded during these months: 37.8 °C and 37.1 °C, respectively, showing a variability of 6.3 and 4.7% between 2000 and 2009.

In a statistical analysis of data numerical description, the normal distribution of monthly energy consumption average values is observed, also summer consumption, and February consumption (Fig. 16). Graphics show position measures (average) and dispersion (standard deviation). Normal distribution is defined by the location of data between ±3 standard deviation.

During the monitoring period, February 2010, the absolute maximum temperature was 36.2 °C (almost 1 °C below the 2000–2009 average) and the monthly energy consumption was 301.5 kWh, which comes close to the historical monthly average consumption.

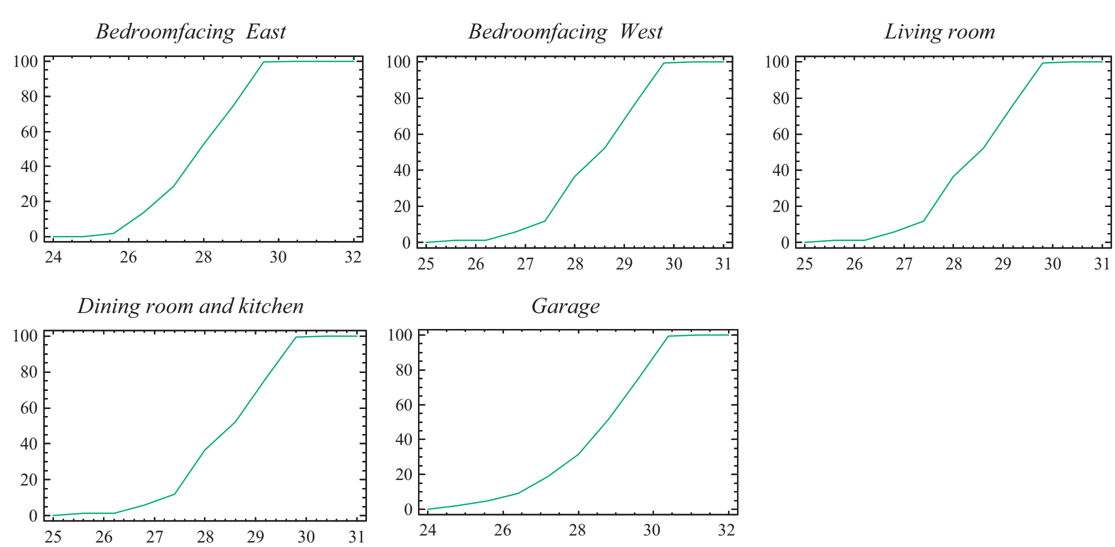


Fig. 14. Percentage of hours with temperatures higher than 26.5 °C in C3.

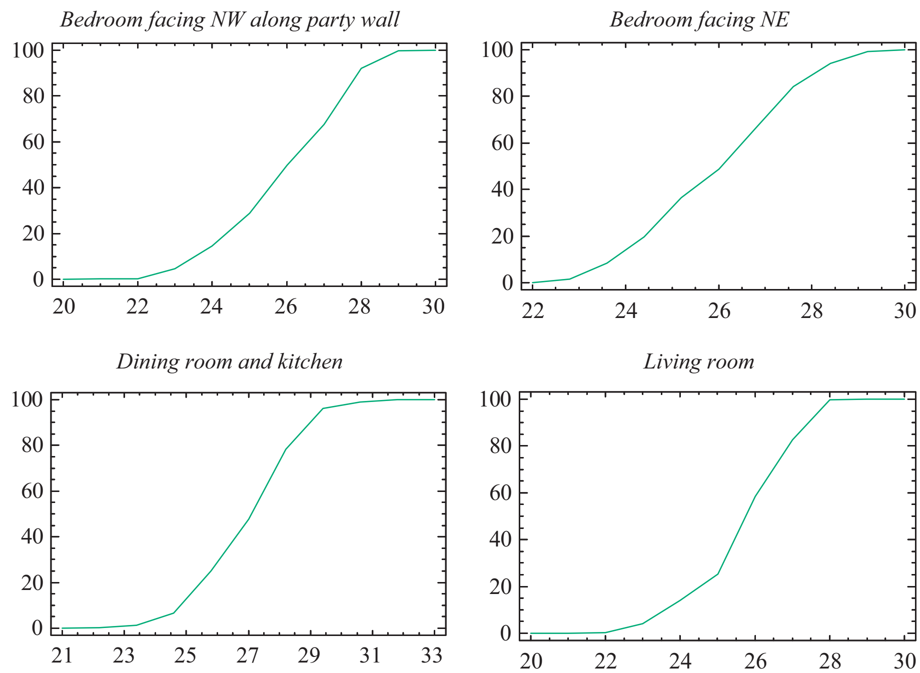


Fig. 15. Percentage of hours with temperatures higher than 26.5 °C in C4.

Table 2
Historical annual and monthly electricity consumption in C1 during the period 2000–2009.

	Years	1	2	3	4	5	6	7	8	9	10	Statistical indicators		
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average	SD	CV
Electricity consumption (kWh)	Annual	2947.0	3467.0	3442.0	2891.0	2988.0	3113.0	3178.0	3193.0	2682.0	3350.0	3125.1	253.2	8.1
	Monthly average	245.6	288.9	286.8	240.9	249.0	259.4	264.8	266.1	223.5	279.2			
	SD	28.1	42.4	45.4	48.0	35.8	35.5	22.4	49.3	70.3	52.7			
	CV (%)	11.4	14.7	15.8	19.9	14.4	13.7	8.5	18.5	31.5	18.9			

The daily average consumption was 10.8 kWh, close to the daily average recorded between February 5 and 17 (11.8 kWh). In accordance with Fig. 17, statistically, electricity consumption in February had a normal distribution and low variation coefficient; thus it is possible to infer that, in previous years and with mechanical air conditioning, the dwellers lived within comfort limits.

Table 4 shows the historical annual average consumption of the C2 house (2107.1 kW). The variation coefficient for the period 2000–2009 was 9.6%. Table 5 shows the historical monthly average consumption for February (186.8 kWh,) and the variation

Table 3
Monthly average and annual variability electricity consumption in C1 (period 2000–2009).

	Average	SD	CV
January	330.7	60.0	18.1
February	299.8	62.3	20.8
March	265.8	40.7	15.3
April	233.2	43.5	18.7
May	230.7	24.5	10.6
June	257.8	31.7	12.3
Juky	269.3	15.6	5.8
August	260.4	24.0	9.2
September	243.9	30.2	12.4
October	238.7	34.6	14.5
November	232.1	43.9	18.9
December	262.7	40.3	15.3
Annual	3125.1		
Monthly average	260.4		
SD	29.8		
CV	11.5		

coefficient. The CV of monthly average consumption during the period 2000–2009 is 5.6%, a value 49% lower than the one shown for C1 with electrical air conditioning. In the same way as in the previous case, the statistical analysis of data numerical description between 2000 and 2009 shows the normal distribution of the monthly average consumption values, summer consumption, and more specifically, February values (Fig. 16). During February 2010, monthly energy consumption was 205 kWh, 9% higher than the historical average value. The daily average consumption was 7.3 kWh, 0.82 kWh above the recorded value. It can be inferred that the house dweller, which has no mechanical air conditioning in the house, had similar living habits along the previous years, basically regarding natural ventilation of rooms, times to open windows and watering outdoor surfaces. As reflected by the previous case, consumption during February also has a statistically normal distribution (Fig. 17).

House C3 (facing west) in the period 2005–2009 had an annual average consumption of 1211.8 kWh. The variation coefficient is 10.5% (Table 6). Table 7 shows the monthly average consumption for the period, of about 102.8 kWh and a variation coefficient of 10.4% along the year. In the same table it is observed an increase in variation between June and October and amongst years. It may be possible, too, that this variability be associated to clear sky and natural light availability during those months with less sunlight hours and electricity consumption to illuminate rooms. As it happened in previous cases, the statistical analysis of data numerical description between 2005 and 2009 shows a normal distribution of monthly average consumption values, summer consumption and, particularly, February (Fig. 16). During the monitoring period (February 5–17) monthly energy consumption was 113 kWh,

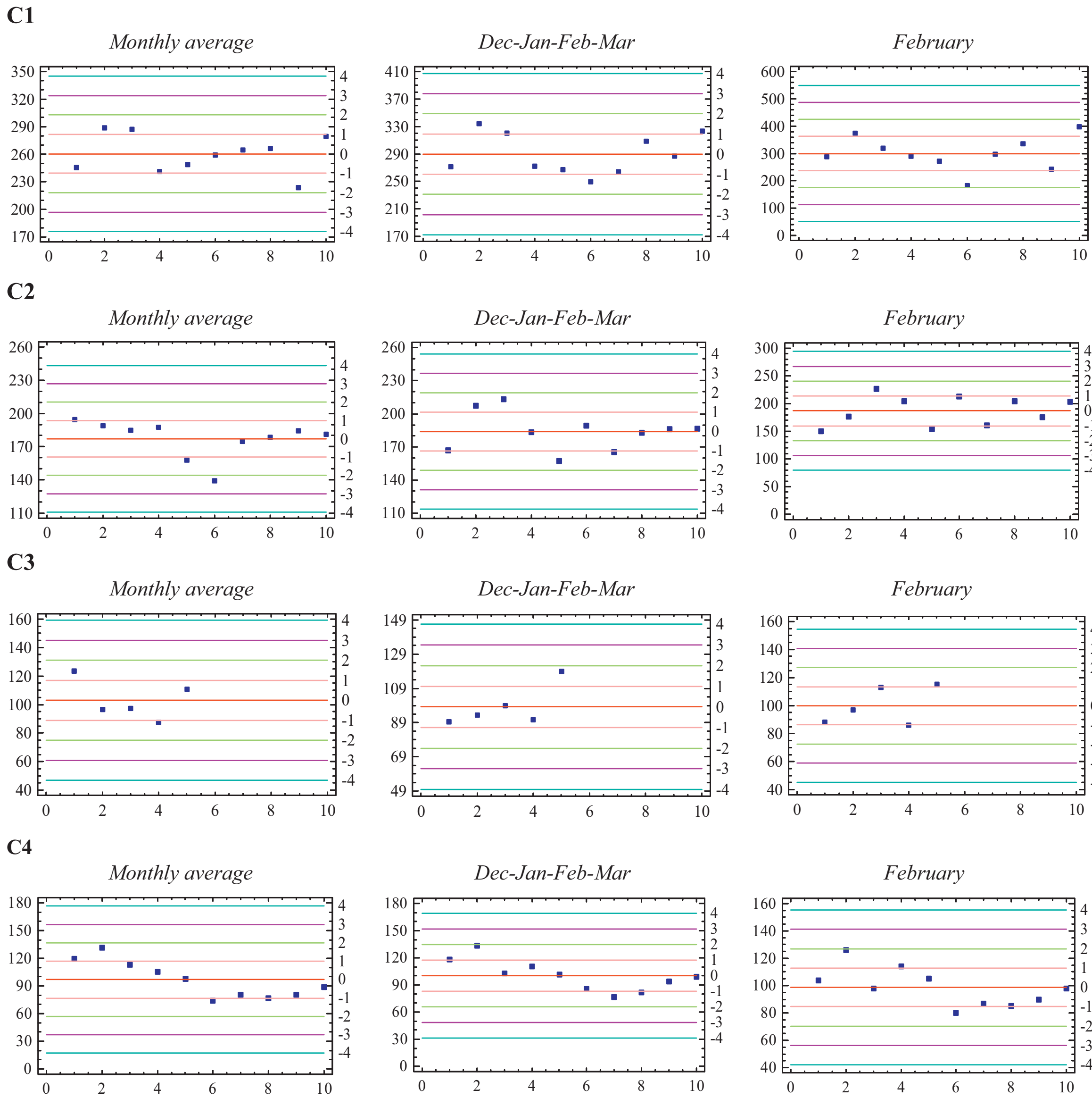


Fig. 16. Statistical analysis of normal performance of historical electricity consumption during the period 2000–2009. *References*: axis *X*: years between 2000 and 2009; primary axis *Y*: real electricity consumption (kWh); secondary axis *Y*: standard deviation.

figure that comes close to the historical value, and this makes us think that the dwellers' living habits were similar to the ones observed during the monitoring period in February 2010. The daily average consumption was 4 kWh (Fig. 17).

Finally, house C4 (facing south) recorded an electricity annual consumption of 1161.6 kWh and a variation within the period of 20.6% (Table 8). The monthly average consumption was 96.8 kWh and the variation of historical monthly average consumption was 8.8% (Table 9). Consumption recorded during the monitoring period (February 2010) was 170 kWh, with a daily average consumption of 6.1 kWh. Energy consumption was 42.6% above the historical average (during 2000–2009) of 98.7 kWh, with a daily average consumption of 3.5 kWh. Fig. 17 shows precisely, consumption during February 2010 as an out-layer. This increase in consumption is the result of adding a split air conditioner in the NE bedroom.

When monitoring results from 2010 are added to the statistical analysis, it is observed that the annual behaviour is similar to that of 2009 for C1, C2 and C3. In C4 and during February the asymmetry values fall out of the ±2 range; this shows significant deviations from the normal pattern and would tend to overturn the statistical

Table 4
Historical annual and monthly consumption of electricity in C2.

	Years	1	2	3	4	5	6	7	8	9	10	Statistical indicators		
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average	SD	CV
Electricity consumption (kWh)	Annual	2330.0	2267.8	2217.0	2248.0	1896.0	1672.0	2097.0	2139.0	2211.0	1993.0	2107.1	201.7	9.6
	Monthly average	194.2	189.0	184.7	187.3	158.0	139.3	174.7	178.2	184.2	181.2			
	SD	25.5	33.7	42.6	23.0	5.9	54.4	22.8	22.7	16.2	23.1			
	CV (%)	13.2	17.9	23.0	12.3	3.8	39.1	13.0	12.7	8.8	12.8			

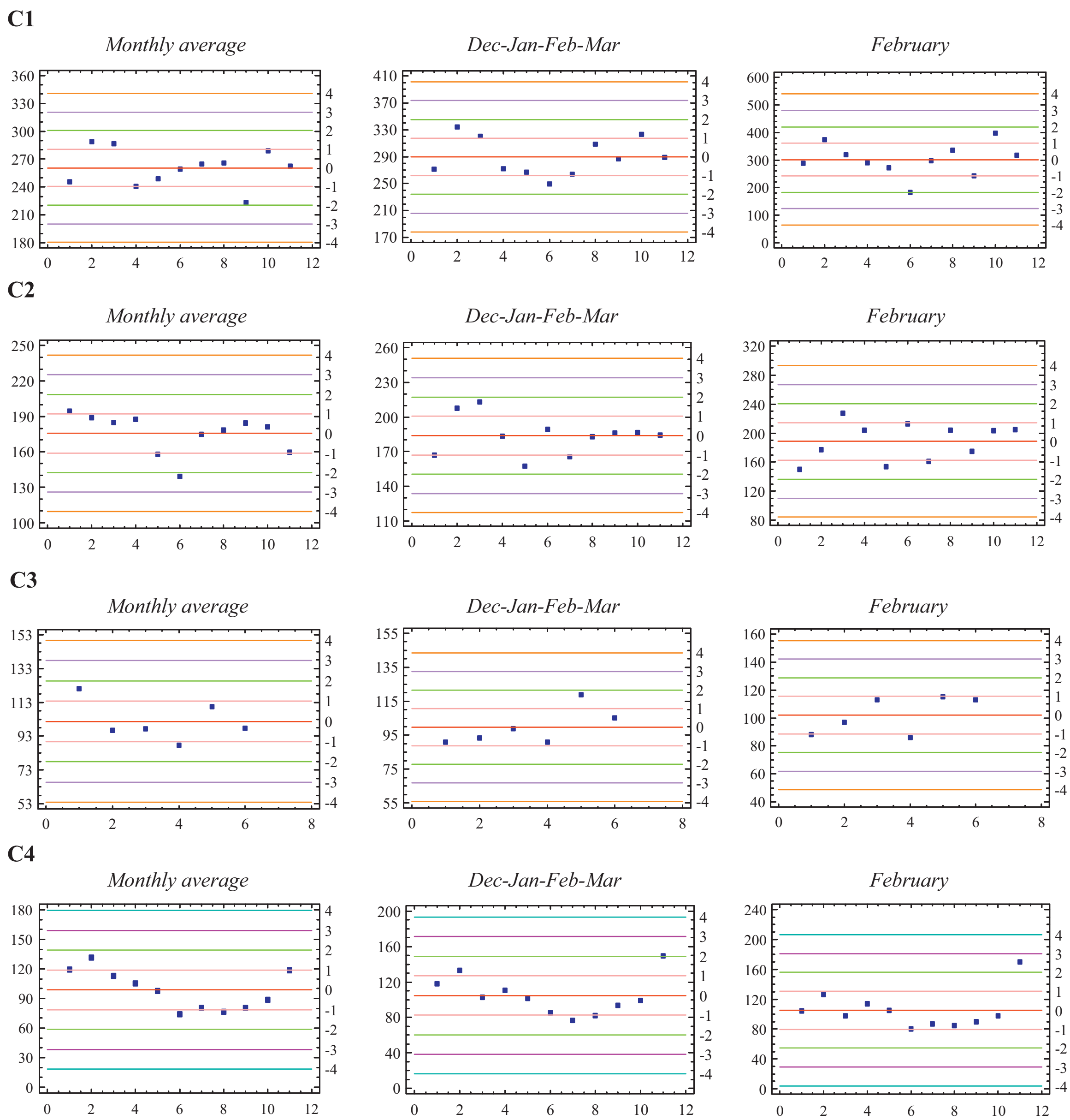


Fig. 17. Statistical analysis of normal performance of historical electricity consumption during the period 2000–2010. *References*: axis *X*: years between 2000 and 2009; primary axis *Y*: real electricity consumption (kWh); secondary axis *Y*: standard deviation.

Table 5
Monthly average and annual variability consumption of electricity in C2 (period 2000–2009).

	Average	SD	CV
January	199.0	41.4	20.8
February	186.8	26.8	14.4
March	174.7	13.7	7.8
April	171.3	19.2	11.2
May	163.3	25.5	15.6
June	181.9	17.8	9.8
Juky	183.8	24.5	13.3
August	176.1	34.9	19.8
September	194.6	21.0	10.8
October	191.6	22.4	11.7
November	172.2	23.2	13.5
December	174.9	33.5	19.1
Annual	2124.2		
Monthly average	177.0		
SD	9.94		
CV	5.61		

analysis regarding standard deviation. The 2010 value corresponds to the highest energy consumption obtained for electrical conditioning use.

As regards the annual average consumption by useful surface square metre, C1 and C2 consumed 22 and 23 kWh/m^2, respectively. C1 has electric mechanical conditioning and C2 has an underground pump to water outdoor spaces. C3 and C4, without electrical air conditioning during summer, consumed 15 and 14 kWh/m^2 during the period 2000–2009, respectively.

During the monitoring period, the daily average consumption recorded in C1, according to previous information above, was 11.8 kW: lighting (12.7%), big electrical appliances (42.3%) and the remaining 45%: mechanical air conditioning. In C2 the daily average consumption was 6.5 kWh. 23% corresponded to the use of the watering pump (2HP during 1 h), 65% was used in lighting and 12% corresponded to the use of big electrical appliances. The C3 house had a daily consumption of electricity of 3.9 kWh (0.056 kWh/m^2). Lighting and appliances absorb 17% and 63%, respectively. C4 consumed 5.6 kWh distributed in the following

Table 6
Historical annual and monthly consumption of electricity in C3.

	Years	1	2	3	4	5	Statistical indicators		
		2005	2006	2007	2008	2009	Average	SD	CV
Electricity consumption (kWh)	Annual	1377.0	1157.0	1167.0	1051.0	1327.0	1215.8	133.6	11.0
	Monthly average	114.8	96.4	97.3	87.6	110.6			
	SD	49.3	9.3	16.3	10.0	14.0			
	CV (%)	42.9	9.6	16.7	11.5	12.7			

Table 7
Monthly average and annual variability consumption of electricity in C3 (period 2005–2009).

	Average	SD	CV
January	91.4	47.3	51.8
February	99.8	13.6	13.7
March	91.6	9.9	10.9
April	94.8	11.6	12.2
May	95.4	5.8	6.1
June	109.6	31.4	28.7
Juky	118.6	48.5	40.9
August	109.0	29.3	26.9
September	120.8	27.8	23.0
October	86.8	19.0	21.9
November	102.0	8.9	8.8
December	96.0	14.0	14.6
Annual	1215.8		
Monthly average	101.3		
SD	10.9		
CV	10.8		

Table 9
Monthly average and annual variability consumption of electricity in C4 (kWh) during the period 2000–2009.

Month	Average	SD	CV
January	116.8	19.3	16.5
February	98.7	14.1	14.3
March	94.6	20.7	21.9
April	64.9	27.8	29.3
May	87.3	29.5	33.8
June	103.2	25.5	24.7
Juky	103.1	23.0	22.3
August	101.7	25.0	24.6
September	93.7	19.6	20.9
October	88.9	33.4	37.5
November	87.8	24.2	27.6
December	90.9	30.5	33.6
Annual	1161.6		
Monthly average	96.8		
SD	8.5		
CV (%)	8.8		

way: lighting, approximately 12%, big appliances 57% and electrical air conditioning 31%. The same house, until 2009 without electrical conditioning, consumed 3.5 kWh/day, out of which 18.6% corresponded to lighting and 81.4% to the use of big appliances.

Table 10
Reference houses.

Houses	2000–2009 (kWh/m^2)		February 2010	
	Annual	February	kWh/m^2	kWh/d
C3	10.4	0.9	0.9	4.0
C4	17.0	1.2	2.0	5.6

6. Extrapolation of results to a sector in the neighbourhood. Pilot plan

Results obtained allowed us to question whether there would be a possibility of technological intervention to improve comfort conditions and decrease energy consumption. To provide an answer to these questions we designed as pilot plan the extrapolation of results obtained in one sector of "Villa del Busto" where there are two houses that had been monitored (C3 and C4). By means of direct observation of each of the blocks we could detect houses sharing the same characteristics as those used as reference (Fig. 18). We added to our analysis, only those which have uninterrupted electricity historical consumption records since 2000 and which show low variation coefficient amongst years, data guaranteed by the permanence of the same family. Details regarding the area of each of the houses were obtained from the General Land Registry of the province.

Table 10 shows a synthesis of the results obtained in the houses used as reference: C3 and C4. Until 2009 and during February they had an electricity consumption of 0.9 and 1.2 kWh/m^2, respectively. During 2010 the value increased in C4 to 2.0 kWh/m^2 due to the fact that a split conditioner was added, and it remained the same in C3. Previous results showed that C3, without mechanical conditioning, presented the most unfavourable thermal behaviour. Dwellers in this house were 90% of the time in discomfort in the kitchen/dining-room area, value that in C4 decreased to 70% due to the effect of the mechanical conditioning. It is evident that even this last value needs to be reduced.

The extrapolated data can be observed in Table 11. In the samples, the houses facing west prevail. It is possible to infer that, with the exception of the house at 275 Catamarca St., all the others might have mechanical climatisation, and they show a consumption of between 1.4 and 2.3 kWh/m^2 and 5.6 and 10.5 kWh/day, values that, not necessarily guarantee comfort conditions along the day. It may be relevant then, to study alternatives that may bring about comfort conditions while at the same time minimize energy consumption. We propose as a hypothesis a technological type of intervention: the party walls do not collect energy, most of the houses have shaded facades and low roller shutters during sunlight hours, and their roofs appear as the most vulnerable part from an energy perspective.

Table 8
Historical annual and monthly average consumption of electricity in C4 (kWh).

	Years	1	2	3	4	5	6	7	8	9	10	Stadistical indicators		
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average	SD	CV
Electricity consumption (kWh)	Annual	1431.0	1581.0	1359.0	1266.0	1169.0	887.0	969.0	920.0	969.0	1065.0	1427.0	240.8	20.3
	Monthly average	119.2	131.7	113.2	105.5	97.4	73.9	80.7	76.7	80.7	88.7			
	SD	9.7	15.3	14.0	8.4	19.3	24.2	10.6	21.8	21.4	18.0			
	CV (%)	8.2	11.6	12.3	8.0	19.8	32.7	13.1	28.4	26.5	20.3			



Fig. 18. View of the studied houses in the results' extrapolation.

In accordance with what was set forth by Verbeeck and Hens [39], we consider that the most economic and simple intervention to carry out in order to improve the current condition is to insulate the roof. IRAM Norm 11605 recommends three levels: A, B and C with K values of 0.19, 0.48 and 0.76 W/m^{2,} respectively. In order to quantify savings we take the C3 house as reference with an original roof thermal transmittance of 1.52 W/m^2 °C. By applying the *Simedif for Windows* software [38] it is possible to determine the cooling load for a thermostat indoor temperature of 25 °C. Results obtained show that the reference house would have a cooling load of 12.6 kWh/day and 1.2 kWh/m^2. The cooling load in a house with a thermally improved roof (K = 0.48 W/m^2 °C) would be 10.3 kWh/day and 0.98 kWh/m^2. Energy saving in cooling for an indoor temperature of 25 °C is 18%.

Table 11
Studied houses in the results' extrapolation.

House (address)	Facing	2000–2009 (kWh/m^2)		February 2010	
		Annual	February	kWh/m^2	kWh/d
350 Brown	W	26.9	2.3	2.2	10.5
268 Catamarca	S	22.6	2.3	2.3	7.9
275 Catamarca	N	12.3	0.9	0.9	4.5
225 T. Mason	E	22.8	1.8	2.0	5.2
368 Brown	W	15.1	1.2	1.4	7.7
284 Estrada	W	10.3	1.3	1.6	6.0
382 Estrada	W	18.3	1.7	2.1	8.8
337 Estrada	E	11.5	1.3	1.7	5.6

An urban block for this study has approximately 40 houses. According to values in the reference house, 504 kWh are required daily. For 30 cooling days and 100 blocks in the urban area under study the value would be 151,2000 kWh, corresponding to the annual consumption of 700 users (2134 kWh). That means 18% saving during sunlight hours in the whole neighbourhood, a figure that can be considered highly promising.

7. Conclusions

This work allowed us to analyze the thermal behaviour in four compact houses located in low-density neighbourhoods, in which one-floor buildings with a typology similar to the studied ones prevail. The houses are compact, they are located between party walls, they present different orientations and their users have different living habits. Recordings were performed simultaneously. Climatic conditions along the period were very harsh. It must be pointed out that the dwellers adopted natural climatisation strategies: cross-ventilation, sun protection during summer over the areas mostly affected by solar irradiance, shading with plant covers, watering at adequate times, etc. Indoor temperature behaviour, energy consumption during the same recording period and comfort conditions were analyzed. In a second phase, two out of four houses were selected and those values were extrapolated to blocks in the neighbourhood in which they are located.

C3 was the house which presented the most unfavourable conditions, with its façade facing west and receiving important solar radiation on its roof. Its west wall does not receive the necessary shading from trees and so it would not meet the requirements in Fig. 2, which states that from 11:00 am until 7:00 pm surfaces must be shaded during January, February and March, November and December. The house has a roof fan which was only turned on during times of use at the dining-room and whose monitoring showed that during 90% of the time, users would be in a situation of discomfort. In the harshest hours along the day, which we infer are those during which dwellers rest; users would be in a situation of discomfort too. In this house, natural ventilation was limited to those days in which there was not suspended dust in the air, a characteristic of the climate in times of drought. C1, with its façade facing north and electrical conditioning showed a more favourable situation in the sleeping areas and also in the sitting-room, but despite the fact the kitchen/dining-room has mechanical conditioning and little natural ventilation, it appeared as the hottest area and temperature was only 20% of the time below 27 °C. In C2, with natural climatisation, the kitchen/dining-room showed temperatures that were 80% of the time below 27 °C. Night cross-ventilation and thermal mass favoured the natural climatisation of the house. The C4 house, with a split air conditioner used 1.3 h. per day, showed that only 40% of the monitoring time in the kitchen/dinning-room, users were in a situation of comfort. This house has a façade facing north and leading to the back yard which is well protected by plants following the design recommendations of Fig. 2.

Results obtained showed that the users of these houses with the detailed technology and typology would not reach comfort conditions without mechanical conditioning. Extrapolation of results to houses in other parts of the block allowed us to infer -analyzing electricity consumption patterns- that dwellers did not live in comfortable conditions. The search for a solution constitutes a pressing matter. In agreement with Verbeeck and Hens [39], we consider that roof insulation as first step is the simplest and most economical measure to be taken to improve this condition; this together with the natural climatisation strategies already implemented by users as part of their daily routines would permit an energy consumption reduction, improving at the same time comfort levels. Results also showed that only if thermal transmittance Level B – recommended by IRAM Norm – were reached, energy saving during sunlight hours to keep an indoor mean temperature of 25 °C would be 18%. Energy saving in the neighbourhood under study would correspond to the annual average consumption of 700 residential dwellers (2134 kWh/year).

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